Research on Attitude Pursuit Guidance Law for Strapdown Homing System

SONG Jian-mei
(School of Mechano-Electronics Engineering, Beijing Institute of Technology, Beijing 100081, China)

Abstract: This paper comprehensively analyzes the attitude pursuit guidance law which is one of the simple guidance methods for strapdown homing guidance system. Via the analytical solution of attitude pursuit, limitations on the velocities of missile and target are presented. The influence of damping, lagging and transfer parameter from rudder deviation to angle of attack on the attitude pursuit guidance law is discussed by using Automatic Control Theory. It is concluded that the velocities of missile and target should not be too large, and the stable loop of missile body should have some damping when the missile guidance system has inherent lagging, and the transfer parameter mentioned above should not be too large when the attitude pursuit guidance law is used.

Key words: strapdown homing guidance; attitude pursuit guidance; damping; lagging; missile

捷联寻的制导系统弹体追踪导引方法研究. 宋建梅. 中国航空学报(英文版), 2004, 17(4): 235-239.

摘 要: 对捷联寻的系统的简易制导方法—弹体追踪法进行全面剖析,解析分析了弹体追踪法对导弹速度、目标速度的约束,以及弹体阻尼、滞后、舵偏到攻角之间的传递系数对弹体追踪导引性能的影响。通过数学推导及应用控制理论分析与仿真,弹体追踪法较比例导引和速度追踪法在导引特性和打击机动目标时性能较差,但其成本较低,是一种降低制导武器成本的简易制导方法。但采用弹体追踪法时,导弹和目标的速度不能太大,当制导武器系统在形成导引误差信号存在固有滞后时,弹体稳定回路需要有一定阻尼,且舵偏到攻角之间的传递系数不能太大,即飞行过程中攻角要较小。

关键词: 弹体追踪; 阻尼; 滞后; 捷联寻的; 导弹
文章编号: 1000-9361(2004)04-0235-05 中图分类号: TJ765.22 文献标识码: A

Strapdown guidance technology is one of the main ways to reduce the cost of guided weapon and to remake regular ammunition. It makes the seeker strapped down to the missile body directly, and omit the gimbal of conventional seeker and initial space-stabilizing platform. So the seeker has no complicate mechanical structure and the reliability of the guidance system is strengthened.

So the defense industries and army forces of many countries lay great emphasis on the strapdown seeker and strapdown homing guidance technology. Much interest is added to this field with the fast development of micro-optical-electrical technology and innovation of microcomputer[1].

This paper mainly studies the attitude pursuit guidance (APG) method which is one of the available simple guidance law for strapdown seeker, and focuses on its guidance performance and its limitations on the missile system.

Firstly this paper makes a comparison of APG, velocity pursuit guidance (VPG) and proportional navigation (PN), then the paper presents the limitations of attitude pursuit on missile velocity and target velocity through the analytical solution of attitude pursuit. The paper also discusses the influence of damping of missile body, system lagging and transfer parameter from rudder deviation to angle of attack via the classical control theory. Finally the paper gives a simulation of some guided ammunition which uses APG law with information provided by its strapdown seeker.

Received date: 2004-03-10; Revision received date: 2004-09-10

1 Comparison of APG Law with other Guidance Methods

The APG law is a guidance method that the longitudinal axis of missile body is needed to point to the target all the time while the missile is attacking the target.

Assuming that the missile body is well damped, and via simulation, the angle relationships among longitudinal axis of missile body, velocity vector and line-of-sight (LOS) can be got, and are shown in Fig. 1.

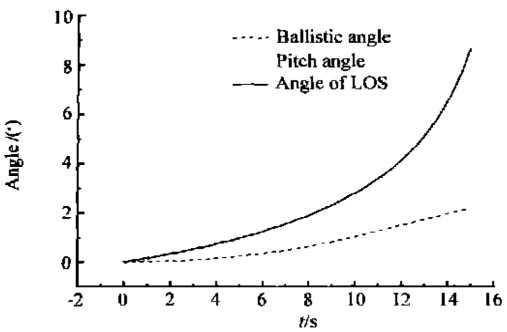

Fig. 1 Angle relationships of APG

From Fig. 1 it can be seen that the longitudinal axis of missile body is required to point to the target, however the longitudinal axis of missile body usually lags behind the LOS and the velocity vector lags behind the longitudinal axis of missile body because of inherent inertial lag in missile system. So the response of guidance system is slow and the missile system can not effectively hit the maneuvering target.

Velocity pursuit guidance (VPG) law[2,3] is that the direction of missile velocity is required to point to the target while missile is attacking the target. The angle relationships among longitudinal axis of missile body, velocity vector and LOS are shown in Fig. 2 after simulation.

When using VPG, the direction of missile velocity usually lags behind LOS, but this lag is much smaller than the velocity lagging of APG. Therefore the ability to hit the maneuvering target and its guidance performance are better than the APG's.

When using proportional navigation (PN)[4] and with larger navigation coefficient, the angle relationships among longitudinal axis of missile body, velocity vector and LOS can be got after simulation and are shown in Fig. 3.

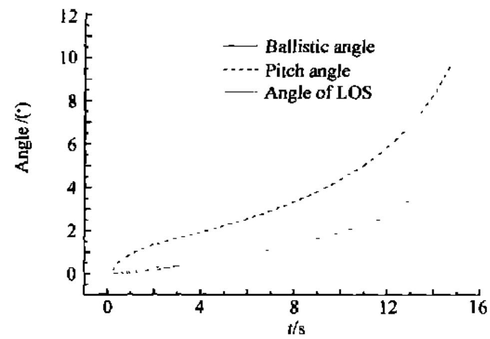

Fig. 2 Angle relationships of VPG

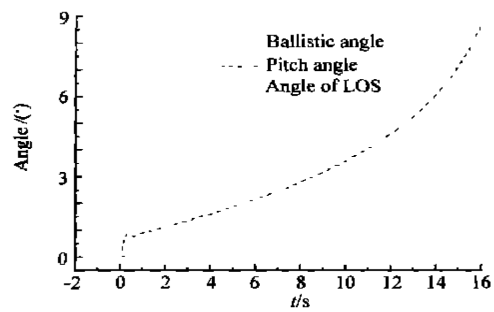

Fig. 3 Angle relationships of PN

The longitudinal axis of missile body leads the direction of velocity and further the direction of velocity leads the LOS when using PN, that is to say, the longitudinal axes of both missile body and velocity all pre-position the LOS. So PN can effectively attack the maneuvering target and its trajectory is also straighter than APG's and VPG's.

From the comparison of the three guidance methods, the performance of PN is the best, however it needs the conventional gimbal seeker to provide the LOS angle rate information. The PN can also be realized via Kalman filter when the missile is equipped with strapdown seeker and INS. So the cost of hardware to realize PN is higher. For VPG, it is necessary to mount vane and strap the detector down to the vane with its center axis parallel to the vane's direction. The hardware cost of VPG is lower than PN's. For APG, it only needs a strapdown seeker, and its hardware cost is the lowest. Although the guidance performance of APG is not

as good as PN's or VPG's, it is no doubt that a low cost and simple guidance law for some weapon system should be considered when the guidance performance requirement is not too high.

2 Limitations of APG on Missile Velocity and Target Velocity

Assuming the missile being a controlled mass point and the target maneuvering along a straight line with constant velocity, as shown in Fig. 4, then the relative motion equations of missile and target are as follows,

$$\left.\begin{aligned} r\frac{\mathrm{d}q}{\mathrm{d}t} &= V\sin\alpha - V_{\mathrm{T}}\sin q \\ \frac{\mathrm{d}r}{\mathrm{d}t} &= V_{\mathrm{T}}\cos q - V\cos\alpha \\ q &= \vartheta = \theta + \alpha \end{aligned}\right\} \qquad (1)$$

where α is the angle of attack; ϑ is the pitch angle; θ is the ballistic angle; q is the angle of LOS; r is the relative distance between missile and target; V is the missile velocity; V_{T} is the target velocity.

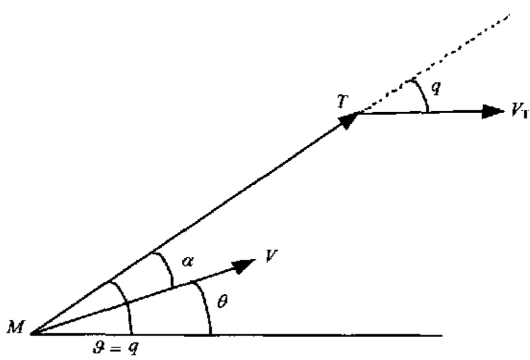

Fig. 4 Relative motion of missile and target when using APG

Assuming that the target is stationary, Eq. (1) can be simplified as

$$\left.\begin{aligned} r(\dot\theta + \dot\alpha) &= V\sin\alpha \\ \dot r &= -V\cos\alpha \end{aligned}\right\} \qquad (2)$$

Furthermore assuming that the velocity of missile changes little, then one of the motion equations of missile is as follows,

$$mv\frac{\mathrm{d}\theta}{\mathrm{d}t} = (P\sin\alpha + Y) - mg\cos\theta$$

that is

$$\dot\theta = \frac{P\sin\alpha + Y}{mV} - \frac{g}{V}\cos\theta \qquad (3)$$

where m is the missile's mass; P is the thruster's push force; Y is the lift force.

Because $\frac{g}{V}\cos\theta$ in Eq. (3) is small, it could be omitted. Then

$$\dot\theta \approx \frac{P\sin\alpha + Y}{mV} \qquad (4)$$

Substituting Eq. (4) into Eq. (2)

$$r\left(\frac{P\sin\alpha + Y}{mV} + \dot\alpha\right) = V\sin\alpha \qquad (5)$$

Because the angle of attack α is a limited value and usually small for general missile,

$$P\alpha + Y + mV\dot\alpha = \frac{V}{r}mV\alpha$$

Since

$$Y \approx C_{y,\alpha}\alpha qS + C_{y,\delta_Z}\delta_Z qS = K_1\alpha + K_2\delta_Z$$

then

$$\dot\alpha = \left(\frac{V}{r} - \frac{P + K_1}{mV}\right)\alpha - \frac{K_2}{mV}\delta_Z \qquad (6)$$

where $C_{y,\alpha}$ is derivative of lift force coefficient with respect to attack angle; C_{y,δ_Z} is the derivative of lift force coefficient with respect to elevator rudder; S is the reference area; δ_Z is the elevator rudder; q is the dynamic pressure coefficient of air.

It can be seen from Eq. (6) that the angle of attack will diverge with the decrease of r. That is, $\alpha \to \infty$ at the impact point.

When the missile is far from the target, even though the missile velocity is very large, in Eq. (6), there will be

$$\frac{V}{r} > \frac{P + K_1}{mV}$$

and then the angle of attack will diverge. When $V_{\mathrm{T}} \neq 0$, and the target is maneuvered along a straight line with constant velocity,

$$P\alpha + K_1\alpha + mV\dot\alpha = \frac{mV}{r}(V\alpha - V_{\mathrm{T}}\sin q) \qquad (7)$$

From Eq. (7), it can be seen that

$$mV\dot\alpha = \underbrace{\left(\frac{mV^2}{r} - P - K_1\right)\alpha}_{A} - \underbrace{\frac{mVV_{\mathrm{T}}}{r}\sin q}_{B} \qquad (8)$$

If the missile velocity is too large or the distance between missile and target is too short, part A in the above equation will make α diverge with time exponentially. If the velocity of missile and

target are all too large and r is too small, part B in the above equation will make α diverge with time monotonously. Therefore, the APG is only used to the guided weapon system in which missile velocity and target velocity are slower, and the initial distance between missile and target is long enough.

In all, when the target is stationary and APG is used in the missile system, the angle of attack of missile is divergent with the decrease of relative distance, and tends to infinity at impact time. Since the real angle of attack of missile is limited, the missile has already diverted the required trajectory before hitting the target, and APG can not be realized ideally. So APG only can be used under the in which the velocity of both the target and missile are low, and while the initial relative distance is long enough.

3 The Influence of Parameter of Missile Body and Lagging on APG

This section will utilize Automatic Control Theory to analyze the influences of missile body's damping, system lagging and transfer coefficient on APG.

The non-linear factors, such as saturation of rudder and overload are not considered for convenience, and the LOS angle is assumed as an unit-step signal, then the APG loop is built. Through analyzing its stable margin and close-loop unit-step response, the paper presents the limitations of APG on the missile system design.

(1) Influence of damping on APG's performance

For convenience, the signal-processing lag of seeker is not considered temporally and the transfer coefficient from rudder deviation to attack angle is 2.

When the damping coefficient is $\zeta = 0.1$, the stable margin is as small as 7.89°, and the vibration and overshoot of step response are large.

When $\zeta = 0.3$, the margin of APG's stable loop is 27.6°.

When $\zeta = 0.5$, the stable margin of APG's guidance loop is 47.1°.

From many simulations, it can be seen that when the damping is small, the stable margin of APG's guidance system is also very small. If guidance system has inherent lagging at the same time, the guidance system will be divergent. The stable margin will increase with the increasing of system damping, however the degree of improving is limited.

(2) Influence of transfer coefficient on APG

When $\zeta = 0.3$ and the transfer coefficient from rudder deviation to angle of attack is 0.8, the stable margin of APG's guidance loop is 53.9°. Compared with the condition when $\zeta = 0.3$ and the transfer coefficient from rudder to attack angle is 2, the stable margin was dramatically increased.

It can be concluded that the transfer coefficient from rudder to attack angle should not be very large in order to insure the stability of APG's guidance loop, in other words, the difference between pitch angle and ballistic angle should not be too large, which presents the limitation on the missile system design.

(3) Influence of lagging of APG

When $\zeta = 0.5$ and the transfer coefficient from rudder deviation to attack angle is 2, the stable margin of APG's guidance loop is about 47° if the lagging is not considered. However, when the lagging is added and its lagging time is $\tau = 0.025$s, the stable margin is 3.95°, and the guidance is near to the critically stable condition. The lagging time will vary with the different work principles of strapdown seeker.

When $\zeta = 0.5$ and the transfer function from rudder to attack angle is 0.8, and also the system has inherent lag as $\tau = 0.025$s, the stable margin is 37°.

It can be seen that decreasing the transfer coefficient from rudder deviation to angle of attack will dramatically strengthen the stability of APG's guidance loop and overcome the negative influence of lagging.

4 Simulation of APG Used in Some Guided Ammunition

This section gives the simulation results of some guided ammunition using APG, where the cross maneuvering of target is assumed as $V_T =$

5m/s, and $\zeta = 0.3$, and the lagging time is $\tau = 0.05$s, the transfer coefficient from rudder deviation to angle of attack is 0.4. The simulation result are demonstrated in Figs. 5– 8, and the miss-distance of the simulation is about 1m.

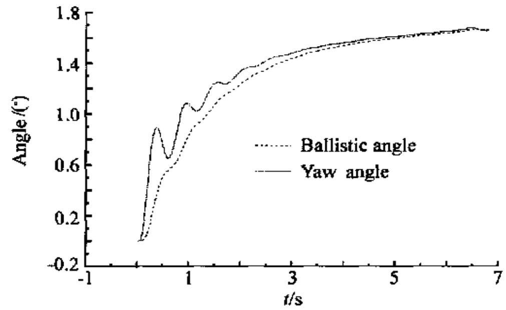

Fig. 5 Angle variation curves with time

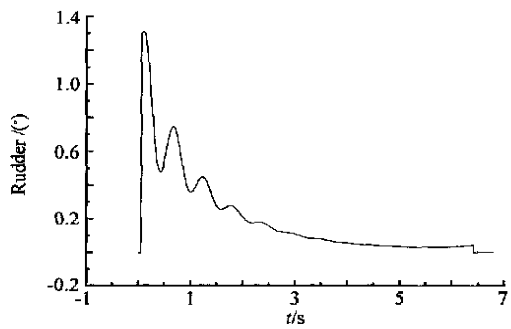

Fig. 6 Variation of rudder deviation with time

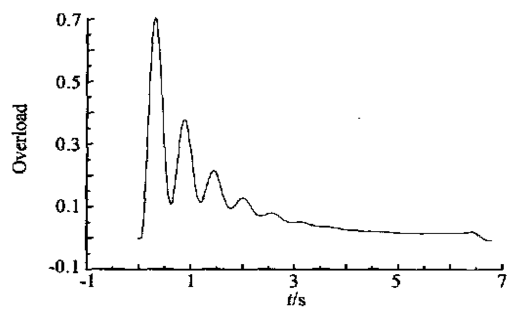

Fig. 7 Overload-time curve

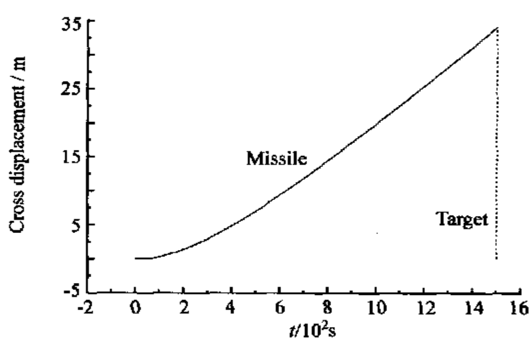

Fig. 8 Motion trajectories of missile and target

It can be seen that the APG guidance law can guide the missile to hit the target accurately, if the transfer coefficient from rudder deviation to attack angle is appropriate, even if the missile has inherent lagging.

5 Conclusions

APG is a low-cost guidance method which needs only a strapdown seeker to measure the target information. On the other hand, it requires that the missile velocity and target velocity are not too large. When the guidance system has inherent lagging, APG requires the missile body to have some damping and the transfer coefficient from rudder deviation to attack angle to be appropriate, that is, the attack angle should be small. These presents the index limitations on missile system design.

References

[1] Thomas R, Callen. Guidance law design for tactical weapons with strapdown seekers[A]. AIAA Guidance, Navigation and Control Conference[C]. Reston VA, American Institute of Aeronautics and Astronautics, 1979. 281– 293.

[2] Gano B C, Meir P. Velocity pursuit guidance for anti-tank missiles with air-vane mounted seekers[A]. Proc Summer Computer Simulation Conf[C]. 1990. 1007– 1101.

[3] Gano B C. Modified velocity pursuit guidance law with crosswind correction for missiles against surface targets[A]. AIAA Guidance, Navigation and Control Conference[C]. Reston VA, American Institute of Aeronautics and Astronautics, 1991. 1566– 1571.

[4] Chadwick W R. Analytical solution of missile terminal guidance [J]. Journal of Guidance Control and Dynamics, 1998, 21(2): 342– 348.

Biographies:

SONG Jian-mei (1968-), an associate professor in the School of Mechano-Electronics Engineering, Beijing Institute of Technology. She received doctoral degree in navigation, guidance and control in 2001. She received MS degree in automation control from Tianjin University in 1994. Her interests include guidance and control system design of tactical missile, variable structure control theory, analysis and identification of non-linear systems, terrain following/avoidance technology, terrain matching technology and strapdown guidance technology, *etc*. E-mail: SJM318@bit.edu.cn